Evolution of the Population of Precipitating Convective Systems over the Equatorial Indian Ocean in Active Phases of the Madden–Julian Oscillation

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ABSTRACT

Three-dimensional radar reflectivity fields from a dual-wavelength Doppler polarimetric radar (S-PolKa) deployed in the equatorial Indian Ocean are used to evaluate the composition of the population of convective cloud elements during active phases of the MJO. Rainfall in active periods was intermittent, occurring in 11 episodes of about 2–4 days, separated by several nonrainy days. Data for these 2-day periods were composited relative to the time of maximum rainfall. Analysis of the S-PolKa data shows the makeup of the convective population during the rainfall episodes. Four types of echo structures were analyzed statistically for the 11 rainfall episodes: shallow convective echoes (SCE), deep convective cores (DCC), wide convective echo cores (WCC), and broad stratiform (BSR) echo regions. SCE and DCC events were most frequent before the maximum rainfall, with the peak frequency of SCE leading that of DCCs. WCCs were most frequent during the rainfall maximum, and BSR regions were most frequent in the later part of the rainfall episode. Composited ECMWF Interim Re-Analysis (ERA-Interim) data and 3-hourly atmospheric soundings indicate that the 2–4-day episodes were related to the passage of equatorial waves. In the early part of a rainfall episode, the wave-passage conditions were unstable, favoring deep penetrating convective elements, while in the later period the wave divergence profile was commensurate with convective systems in late anvil-producing stages. These results support the stretched building-block notion of the life cycle of tropical convection and confirm satellite-based interpretations of SCE, DCC, WCC, and BSR statistics in the composition of the convective population.

1. Introduction

The Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) accounts for a major component of the intraseasonal variability of the tropical general circulation, and it is closely connected with the variation of the convective cloud population over the equatorial Indian Ocean (Zhang 2005). This study uses a series of observational datasets collected during Dynamics of the Madden–Julian Oscillation (DYNAMO) field project and the Atmospheric Radiation Measurement Program (ARM)’s MJO Investigation Experiment (AMIE). These partner campaigns collected data over the Indian Ocean and western Pacific, where the MJO is best defined. The goal was to obtain information that will allow scientists to discern details of the convective cloud field and to relate these details to the large-scale circulation of the MJO.

The 4-month period of data collection in DYNAMO/AMIE was long enough to provide detailed observation of cycles of the convective population during occurrences of the MJO over the Indian Ocean. However, the area of detailed data collection was small, and ultimately the results must be related to the large-scale circulation of the tropics.

To connect the measurements of convective and mesoscale cloud systems in DYNAMO/AMIE to the MJO, it will be necessary to upscale the field data to larger scales of motion. One important pathway for this upscaling is to relate the local observations at the field sites to satellite data, which are global in reach. Ordinary infrared or passive microwave imagery alone is limited in what it can provide in terms of insight into convective clouds in the MJO because it does not provide three-dimensional structural information. Satellites with active radars on board can, however, provide climatological information on the structure of deep convective systems. The Tropical Rainfall Measuring Mission (TRMM) satellite (Simpson and Adler 1988; Kummerow et al. 1998, 2000) has a 2-cm-wavelength precipitation radar on
board, and CloudSat (Stephens et al. 2002) features a millimeter-wavelength cloud radar. One of the limitations of using these tools is the difficulty in determining the probable life cycles of the convective entities producing satellite-based statistics because TRMM and CloudSat sample any given location by using snapshots widely separated in time. One goal of the present study is the use of the excellent time continuity of the field-program measurements to improve interpretations of the statistics obtained with such satellite snapshot data. Yuan and Houze (2010) and Yuan et al. (2011) have used CloudSat combined with infrared and passive microwave data to determine the climatology of mesoscale convective systems over the whole tropics. However, they were able only to identify mesoscale convective systems in the mature stage of development. Their technique cannot identify developing or dissipating systems. The TRMM satellite radar has been used to characterize the climatology of deep convection over continental regions and oceanic regions of South Asia and South America (Houze et al. 2007; Romatschke and Houze 2010; Romatschke et al. 2010; Rasmussen and Houze 2011; Barnes and Houze 2013). The TRMM methodology used in these studies identifies four types of echo objects: shallow isolated echoes (SCE), deep convective cores (DCC), wide convective cores (WCC), and broad stratiform regions (BSR). These papers assume that the four types of echo entities signify deep convective cloud systems in early, middle, and late stages of development. While this assumption seems reasonable in light of the literature on convective cloud systems, it has never been verified by surface-based radar data.

In this study we use ground-based radar data obtained with the National Center for Atmospheric Research (NCAR) S-PolKa radar deployed in the central Indian Ocean near the equator on Addu Atoll in the Maldives to determine the occurrence of SCE, DCC, WCC, and BSR echoes relative to the development in time of rainfall episodes in active phases of the MJO. Our results will show that the frequency distributions showing the occurrence of SCE, DCC, WCC, and BSR echoes peak at a sequence of times, respectively, and that the large-scale environment reflects these shifts in the membership of the cloud population during any given rainfall episode. The results presented in this work thus confirm that that satellite-based statistics on the frequencies of occurrence of the four types of echo objects identified in TRMM radar data indeed indicate where deep convection forms, matures, moves, and dissipates.

Perhaps most importantly, this study also provides physical insight into the connection between the convective cloud population and the larger-scale dynamics of the active phases of the MJO. In particular we will show the multiscale nature of the precipitation in the MJO. The MJO itself is the largest scale. It consists of active phases of about 2–3-weeks duration when convective rain occurs and another 2–3 weeks of dry weather. In DYNAMO it became clear that the rainfall period does not have a continuous nature but is episodic with periods of rain lasting about 2–4 days separated by several days of suppressed conditions, all within an active MJO period. Understanding the precipitating cloud population of the MJO then reduces to the understanding of the 2–4-day episodes of rainfall. The 2–4-day episodes in turn are larger in scale than individual convective elements. Even the largest mesoscale convective systems (MCSs) (Houze 2004) have lifetimes shorter than 2–4 days. The 2–4-day time scale is characteristic of certain types of equatorial waves (Kiladis et al. 2009). We explore the possibility that the population of convective clouds evolves in each 2–4-day period under the control of intermediate-scale equatorial wave. We take advantage of the DYNAMO sounding data along with reanalysis fields to determine how the radar-observed convective population associated with the two to four episodes of rainfall occurring during MJO active phases evolves in concert with 2–4-day wave passages. Equatorial waves of these time scales include 2-day inertio-gravity waves and mixed Rossby gravity waves (e.g., Matsuno 1966; Haertel and Kiladis 2004; Kuang 2008; Kiladis et al. 2009). In this paper, we will present evidence that the convective cloud population behaves in a way that is consistent with the “stretched building block” notion of convective interaction with the large-scale environment, as proposed by Mapes et al. (2006). Those authors hypothesized that “there is a natural selection in the atmosphere for wave packets whose phase structure produces a local, Eulerian sequence of cloud-zone-supporting anomalies that aligns with the convective cloud system life cycle” (p. 26). We will show that the large-scale conditions varying over the DYNAMO/AMIE area on the 2–4-day time scale correspond to a stretching of the convective life cycle, and that evolution of the statistical preference for SCE, DCC, WCC, and BSR radar echoes is synchronized with this synoptic-scale variation as would be expected if the larger-scale wave phases were selectively aligning with convective life-cycle stages.

2. Datasets

The S-PolKa radar was deployed on the island of Hithadoo (0.6°S, 73.1°E), located at the Addu Atoll in the Maldives, from 1 October 2011 through 15 January 2012. The S-PolKa scanning strategy included surveillance (SUR) scans for mapping the entire area of radar
coverage (360° of azimuth) out to a range of 150 km. Data were recorded in azimuth bins of 1°. The SUR scans were conducted at elevation angles ranging from 0.5° to 11.0° (Fig. 1a). Figure 1a shows that the maximum elevation angle for the SUR is limited in altitude such that it can determine the heights of echoes greater than a given height only beyond a certain range. For example, to resolve reflectivity fields up to 8-km height, one can only consider ranges between 41 km and the maximum radar range (150 km). The dot–dashed lines in Fig. 1a indicate three such ranges of 41–150 km for echo heights of 8 km, 51–150 km for 10-km height, and 61–150 km for 12-km heights.

The SUR scans were followed by a set of elevation angle scans at a sequence of fixed azimuths (such elevation scans are known as RHI scans because in the early days of radar they were displayed on a screen known as a “range–height indicator”). Data were recorded in elevation angle bins of 0.5°. RHI scans were designed to record data with fine vertical resolution over the two azimuthal sectors shown in Fig. 1b. The first encompassed most of the northeastern quadrant covering azimuths from 4° to 82° and was designed to record data over a wide oceanic sector that was nearly free of surface clutter. The second, a narrower sector over an oceanic southeastern quadrant that covered azimuths from 114° to 140°, was chosen to match the location of the vertically pointing KAZR radar placed at the Department of Energy (DOE) ARM site on Gan Island (0.7°S, 73.2°E), which was about 9 km from the S-PolKa site. RHI scans were conducted by moving the antenna continuously in the vertical direction so that data could be recorded at angle increments from −0.5° up to a 45° elevation (Fig. 1c). As for the SUR scans, only certain ranges of data coverage were considered (the initial range is indicated by the dot–dashed line in Fig. 1c) because these ranges resolve reflectivity fields up to a given echo height. The entire sequence of SUR and RHI scans was repeated at 15-min intervals.

Figure 1b shows that the horizontal area of RHI scans covers only about 20,000 km². This limited area coverage prevents the identification of broad stratiform regions, which by definition in the present study are at least 40,000 km² in area, with the RHI scans alone. To be able to analyze the behavior of BSRs within the RHI sectors we first identify BSRs using the SUR scans (which cover about 60,000 km²) and then we match the location of a BSR in a SUR scan to the corresponding radials in the RHI scan obtained nearest in time to the SUR scan.

The radar reflectivity data used in this study was the final, quality-controlled S-PolKa dataset from the S-band radar. The data were fully calibrated for noise correction and with atmospheric attenuation applied. Details of the S-PolKa parameters and quality-control procedures are on the website http://www.eol.ucar.edu/projects/dynamo/spol/. The polar-coordinate data for the SUR and RHI scans were interpolated from the original polar-coordinate format to a three-dimensional Cartesian grid using the NCAR Sorted Position Radar Interpolator (SPRINT; Mohr and Vaughan 1979). The grid element size of the Cartesian data is 0.5 km × 0.5 km in the horizontal and 0.5 km in the vertical. The existence of SCE, DCC, WCC, and BSR echo volumes was determined by analysis of the Cartesian interpolated reflectivity fields. A rain classification technique based on the
methodology of Churchill and Houze (1984) as modified
by Steiner et al. (1995) and most recently by Yuter and
Houze (1997) was used. The classification algorithm
was applied to the interpolated reflectivity field at the 2.5-km
level in order to objectively separate the radar echoes
into convective and stratiform components. Parameters of
the Yuter and Houze (1997) version of the algorithm
were tuned specifically for the S-Polka reflectivity field
observed during DYNAMO by testing the algorithm
results against RHI data to minimize false indications of
convective and stratiform echoes. This tuning procedure
is described in Steiner et al. (1995).

The radar-derived precipitation amounts used in this
study are computed using a “hybrid” polarimetrically
tuned version of the reflectivity–rain-rate relation of
\( R = \left( aZ \right)^{1+b} \), where \( a = 0.027366 \) and \( b = 1.44 \) (M. Katsumata
2011, personal communication). Details of the algorithm
and the parameters used for the calculation of rain
amounts are provided at http://www.eol.ucar.edu/projects/
dynamo/spol/parameters/rain_rate/rain_rates.html. The
parameters of the reflectivity–rain-rate relation are still
being refined. However, for this study the absolute
amounts of rainfall are not critical. More important are
the time variation of the rainfall and the subdivision of
rain into convective and stratiform components. Neither
the time variation nor the convective/stratiform separa-
tion is sensitive enough to the exact rain rate to have
any effect on our present results.

Meteorological conditions in the vicinity of the radar
location were obtained from two sources. An ARM
sounding was launched every 3 h at the Gan site. Time
series of wind, temperature, and specific humidity were
interpolated in space from these soundings at 100-m
vertical resolution and were also interpolated in time to
fill in missing data points. European Centre for Medium-
Range Weather Forecast (ECMWF) Interim Re-Analysis
(ERA-Interim) data (Berrisford et al. 2009) were used
to document the synoptic conditions over the region sur-
rounding S-PolKa. Specifically, we used three-dimensional
6-hourly data for zonal, meridional, and vertical wind
components; divergence field; potential temperature;
and specific humidity on a 1.5° × 1.5° grid. Time series
anomalies of each atmospheric field were computed by
subtracting the time mean at each pressure level from
anomalies of each atmospheric field were computed by

3. Definitions of deep convective cores, wide
convective cores, and broad stratiform regions

Following the methodology of Houze et al. (2007),
Romatschke and Houze (2010), and Romatschke et al.
(2010), who examined data from the TRMM radar, we
identify convective and stratiform echoes that develop
extreme characteristics of intensity, height, or horizontal
extent. Specifically, we identify and extract from the
radar echo patterns of DCC, WCC, and BSR echoes as
they were defined in those previous studies. In this study,
we also include a new category for shallow convective
elements.

First, we locate the regions identified as convective
and stratiform echoes by the tuned Yuter and Houze
(1997) algorithm. Within the convective echo region we
determine the following entities:

- SCEs are contiguous three-dimensional reflectivity
echo volumes that have maximum heights lower than
1 km below the 0°C level, which is estimated using the
3-hourly ARM/Gan sounding. This definition is consis-
tent with that used by TRMM 2A23, version 7, rain
product (Awaka et al. 2009) and discussed previously by
Schumacher and Houze (2003). The SCEs represent
small precipitating clouds of shallow to moderate depth
that are located in regions governed primarily by warm
rain processes.

Within the convective echoes seen by S-PolKa, we
also identify the most intense echo cores by extracting
all contiguous three-dimensional echo volumes contain-
ing equivalent radar reflectivity values exceeding 30 dBZ.
For these intense three-dimensional echo objects, we de-
determine the following subsets:

- DCCs are intense echo cores whose maximum heights
are at least 8 km MSL. This category includes young
and vigorous convective cells with strong updrafts.
- WCCs are intense echo cores whose horizontal areas
exceed 800 km². This category captures regions where
intense convective cells have aggregated into meso-
scale areas of active vigorous cells. They are often part
of large MCSs (Houze 2004) in an intensifying stage of
development where individual convective cells merge
together.
- Deep and wide convective cores (DWCCs) are intense
echo cores that fall into both of the previous two
categories, i.e., they are both deep and wide.

The threshold of 30 dBZ used here to define intense
echo cores is lower than that originally used in Houze
et al. (2007) and Romatschke et al. (2010) of 40 dBZ. The
higher value was useful for continental regions; however,
echoes reaching this intensity are rarer over oceans.

\footnote{The best classification results were found running the algorithm
at the 2.5-km level, and using \( a = 10 \), \( b = 64 \), and \( Z_{th} = 40 \) as values
of the parameters in Eq. (B1) of Yuter and Houze (1997). The
thresholds were set to 11 km as background radius and 5 km as the
convective radius.}
Barnes and Houze (2013) have found that the 30-dBZ threshold is more useful over the tropical oceanic environments considered here. The height and area thresholds used here for WCCs and BSRs were chosen after sensitivity analysis of different height–area combinations as will be explained later.

Finally, within stratiform echo regions, we identify one subcategory:

- **BSRs** are those contiguous stratiform radar echoes without any reflectivity threshold that extends over a horizontal area of at least 40,000 km². This category represents parts of mature stage MCSs composed mainly of large stratiform rainy areas (Houze 2004).

4. Occurrence of deep convective echo types during MJO precipitation episodes

a. Overall frequency of events

During October 2011–January 2012 of the DYNAMO/AMIE campaign, three main periods of enhanced precipitation occurred over the S-PolKa area in association with active phases of the MJO over the Indian Ocean. Figure 2 shows the hourly time series of accumulated rain over the region covered by the S-PolKa radar for these three periods: 15–27 October, 16–28 November, and 15–27 December. During these enhanced periods, the rainfall was highly variable on the synoptic time scale (i.e., a few days). The precipitation came in 11 episodes of significant rain accumulation, each with a mixture of convective and stratiform rainfall. These episodes tended to have a 2-day duration and to be separated generally by 2–4 days during active MJO phases; October events tended to occur at 2-day intervals, while in November and December they occurred at 4–6-day intervals. Table 1 shows the total occurrence of convective radar echo entities for the deep and wide categories defined in section 2b and sampled during the three enhanced precipitation periods of the MJO. The statistics are presented using both SUR and RHI scanning strategies and were evaluated for different combinations of vertical heights and horizontal areas for the most intense convective echo cores defined in section 3. Similarly, Table 2 shows the total occurrence of broad stratiform radar echo events for different combinations of horizontal areas. Comparison of the numbers and proportions of echo elements obtained using the different combinations of heights and areas is difficult because both the SUR and RHI scans covered different areas and had different vertical resolutions. Consequently, the numbers of echo elements identified using the two scanning strategies are not distributed in the same proportions. However, the evaluation of different combinations of height–area thresholds gives us confidence when comparing such combinations with the results presented in the next section. Results for the distribution of the frequencies of occurrence of the different forms of

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>Area (km²)</th>
<th>SUR DCC</th>
<th>WCC</th>
<th>DWCC DCC</th>
<th>WCC</th>
<th>DWCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>800</td>
<td>12,502</td>
<td>1</td>
<td>850</td>
<td>6552</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>800</td>
<td>1662</td>
<td>531</td>
<td>289</td>
<td>1456</td>
<td>170</td>
</tr>
<tr>
<td>10</td>
<td>800</td>
<td>158</td>
<td>736</td>
<td>52</td>
<td>778</td>
<td>248</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>172</td>
<td>556</td>
<td>38</td>
<td>815</td>
<td>188</td>
</tr>
</tbody>
</table>

**Table 1.** Number of echo structures observed in each extreme convective category for different height–area combinations during both S-PolKa reflectivity data scanning strategies. Boldface numbers correspond to the selected combination of height–area used for the analysis.

**Table 2.** As in Table 1, but for broad stratiform regions and using SUR scans only.

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>BSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,000</td>
<td>165</td>
</tr>
<tr>
<td>40,000</td>
<td>122</td>
</tr>
<tr>
<td>45,000</td>
<td>93</td>
</tr>
</tbody>
</table>
deep convection (not shown) are not especially sensitive to the choices of thresholds. The threshold choices that we have made led to a total of 1662 (1456) DCC echo entities that reached 8 km or greater in height when evaluated using SUR (RHI) scans. In the same way, 531 (170) WCC echoes covered areas larger than 800 km², with 289 (239) events falling into both DCC and WCC categories, and 122 BSRs with areas of at least 40 000 km². For the shallow convective category a total of 1090 events were identified when using SUR scans and 578 when using RHI scans. A PDF analysis showing the frequency distribution of the horizontal areas covered by the SCE elements yields an area average of about 8 km² with a standard deviation of about 5 km². This result indicates that these echoes are convective in scale and are similar to the shallow isolated convective echoes identified in TRMM data Schumacher and Houze (2003) and Barnes and Houze (2013).

b. Composites of echo occurrence relative to time of maximum rainfall

Figure 3 shows the frequency of occurrence of each type of echo structure found at each hour from 24 h before (negative values) to 24 h after (positive values) the maximum rainfall accumulation (dashed–dotted curve) calculated with (a) SUR and (b) RHI scanning strategy data. The right y axis is for the colored curves. The rainfall accumulation composite is computed by centering each of the 11 rain episodes in Fig. 2 on the time of the maximum of its running-mean curve in Fig. 2.

FIG. 3. Composites of the frequency of occurrence of each of the different types of radar echo structure defined in section 2 during 24 h before (negative time) and after (positive time) the composite maximum in rain accumulation (dash–dotted curve) calculated with (a) SUR and (b) RHI scanning strategy data. The right y axis is for the colored curves. The rainfall accumulation composite is computed by centering each of the 11 rain episodes in Fig. 2 on the time of the maximum of its running-mean curve in Fig. 2.

Table 3 lists these dates and
times. We calculated the composites in Fig. 3 from both SUR and RHI scanning strategies. The results from the two datasets are remarkably similar in the distribution of the frequency of radar echo structures.

Figure 3 shows that SCEs are present at all times but that they peak in occurrence about 12 h prior to the time maximum accumulation. The number of SCEs decreases as the DCC category maximizes about 5–10 h before the time of maximum rain accumulation. The SCEs slowly increase beginning about 12 h after the peak rainfall. After the DCC echoes reach their maximum frequency (about −5 to −10 h), the frequency of events categorized as both deep and wide (DWCCs) increases and reaches a maximum just before the time of maximum in rain accumulation. The peak occurrence of WCCs comes next, with a maximum about 1–2 h after the time of maximum rainfall. There is a secondary peak in the frequency of occurrence of DCCs in RHI scans not observed in the SUR scans, possibly occurring in the RHI sector as a sampling artifact. At 0 h, the broad stratiform regions begin to appear and reach a maximum around +8 h.

The progression of radar echo structures seen in Fig. 3 shows how the convective population changes its character during the 2-day rainfall episode. The appearance first of a mixture between SCEs and DCCs, while the rainfall initially accumulates, indicates that the precipitating cloud population is dominated by shallow and deep convective elements in relatively early stages of development. Then the population of convective elements becomes dominated by intense convective cells (i.e., DCCs) that are separated from each other but are produced by strong deep penetrating local updrafts, indicative of the larger-scale environment now allowing the cells to extend to higher levels. As time progresses, relative to the maximum rainfall, such individual towers aggregate to form interconnected regions of intense convection. The maximum occurrence of WCC echoes following the maximum of DCCs and lagging the maximum in DWCCs indicates that as the rain episode progresses the population of precipitating clouds becomes dominated by intense cells aggregating into larger units, likely to form MCSs. The higher frequency of the wider systems coinciding with the time of highest accumulation of rain is consistent with the well-known fact that rain accumulation is closely related to areal coverage by rain (e.g., Atlas et al. 1990). It is also well known that as MCSs mature and dissipate, the convection composing them produces mesoscale areas of stratiform rain that last for hours and may or may not be attached to the remaining active convection. The maximum frequency of occurrence of BSR echoes in the declining period of the rain episode indicates that the large-scale environment during this later period supported the growth of systems to their most extreme mesoscale stage in which large stratiform regions can occur in association with MCSs. The gradual increase of SCE echo elements in later stages of the rain episode is consistent with the precipitating cloud population returning to its background state as the synoptic-scale wave passes but the MJO active phase continues.

5. Environmental conditions associated with the evolution of radar echo structures during MJO precipitation episodes

To investigate the large-scale environmental conditions supporting the 11 rain episodes occurring during the active MJO phases of DYNAMO/AMIE, we composited data from the Gan soundings and from ERA-Interim variables. The sounding variables provide measurements of the atmospheric conditions in the immediate vicinity of the radar site. We use ERA-Interim variables over a region around the radar site (1.5°S–1.5°N, 72.0°–75.0°E) to indicate conditions over a broader region surrounding the radar.

a. Environmental time composites for rainfall episodes

Figure 4 shows time–height composite plots of potential temperature and specific humidity relative to the maximum in rain accumulation at 0 h for each of the 11 rain episodes seen in Fig. 2 and indicated in Table 3. In addition, a composite of convective available potential energy (CAPE) anomalies for the time variation of the soundings is included in plot. At around −15 h, a shallow layer of positive potential temperature anomalies appears in both time sections (Figs. 4a,b). In addition, the potential temperature anomaly decreases with height at around −10 to −6 h in Fig. 4a and around −15 to −11 h in Fig. 4b. At the same time that the surface reaches a maximum in potential temperature anomalies, the lower-level
specific humidity increases and reaches an anomalous maximum around $-9$ to $-6$ h when calculated using the Gan sounding and around $-12$ to $-9$ h for ERA-Interim data. These data all point to destabilization favoring deeper convection before the maximum in rain accumulation and, accordingly, the CAPE increases during this time. After the maximum in low-level specific humidity, the potential temperature changes to negative anomaly values while the specific humidity anomaly increases with height. When the time reaches the 0 h corresponding to the maximum in rain, the atmosphere cools and becomes moist at midlevels and dry at lower levels. The CAPE decreases, and the environment persists until the surface and the atmospheric midlevels reach a minimum of specific humidity around $+15$ h.

Figure 5 shows time–height composite plots of divergence and vertical velocity calculated using ERA-Interim data in a similar manner to Fig. 4. At $-20$ h, negative anomalies of surface divergence appear and decrease to a minimum (i.e., peak low-level convergence) at around $-10$ h. During this same time period, pressure velocity decreases, indicating enhanced upward motion with a maximum at the 750-hPa level between $-10$ and 0 h. After this time, vertical velocity anomalies increase, and the center of convergence seen at the surface before the maxima in rain shifts upward, reaching the 500-hPa level with a maximum value at $+12$ h. At the same time, the lower levels of the atmosphere become anomalously divergent with maximum values around $+10$ to $+15$ h. This sequence of divergence and vertical velocity sloping upward from negative toward positive lag over the 2-day composite period is consistent with the sequence expected from a westward-propagating equatorial inertial–gravity wave [e.g., see Fig. 4 of Haertel and Kiladis (2004), Fig. 8 of Kuang (2008), or Fig. 11 of Kiladis et al. (2009)]. Sometimes the pattern might be dominated by synoptic-scale easterly waves with longer periods, but their signatures would be expected to be similar but stretched to a somewhat longer period. We calculated separate composites (not shown) for the October, November, and December rainfall episodes. They confirm that the events that occurred in October indeed dominated the anomaly patterns. Other types of waves contributing to the composite, such as 4-day mixed Rossby–gravity waves or synoptic easterly waves due to instability of the wind in the ITCZ region likely occurred in November and December but were too few in number to be easily isolated in the composite.

Figure 6 shows time–height plots for zonal and meridional wind anomalies composited for $-24$ to $+24$ h from the maximum in rain accumulation as composited in Fig. 4. Figure 6a, calculated using the Gan soundings, shows an anomalous low-level easterly wind at around $-20$ h. Around $-12$ h, the wind anomaly reverses to westerly. The anomalous westerly wind is maximum at 850 hPa, just before the maximum in rain accumulation. At the same time, anomalous northerly wind increases with height reaching a maximum at around 700 hPa. After the maximum in rain accumulation, the anomalous westerly wind decreases and reverses again toward an anomalous easterly component at around $+20$ h. The anomalies of zonal and meridional wind calculated using ERA-Interim data (Fig. 6b) behave in a remarkably similar manner, except that the maximum in westerly wind anomaly is reached several hours after the maximum in rain accumulation. The upper-level zonal wind anomalies (i.e., around 200 hPa) in both Figs. 6a and 6b show a similar progression from easterly to westerly anomalies, but the magnitude attains higher values at a later time than their surface counterpart. An increase in low-level westerly wind anomalies as the most intense rainfall propagates has been observed in association
with the passage of MJO related disturbances across the region (Lin and Johnson 1996; Chen et al. 1996; Zhang and McPhaden 2000; Benedict and Randall 2007).

These statistical composite structures during the time period of the rainfall episode are similar to the way that individual deep convective cloud systems behave, but on a longer time scale than an individual cloud system. An individual MCS forms when deep cells occurring separately in early stages aggregate to form mesoscale units of deep convection in the MCS’s midlife stages, and produce a stratiform rain area in its mature to later stages (Houze 2004). The deep cells of the MCS tap into the unstable air in the lower layers of the troposphere. The result is lower-tropospheric convergence and growing convective cells, which then evolve into precipitating stratiform cloud mass that eventually stabilizes the lower levels. An individual MCS typically develops an ascending, sloping layer of airflow feeding it from the convergent zone. The sloping in the convective region of the MCS feeds a large stratiform region, characterized by midlevel convergence. The midlevel inflow descends in connection with sublimation and evaporation of hydrometeors, thus constituting a sloping downdraft. This mesoscale downdraft lies under the upward-sloping ascent layer. These MCS behaviors are well known (Houze 2004), and they are known to occur over tropical oceans. Sloping of mesoscale up- and downdrafts has been seen in MCSs over the western Pacific warm pool (Kingsmill and Houze 1999). These circulation features are like those shown by Moncrieff (1992) to be a natural adjustment to instability in sheared flows. Moncrieff’s theory was posed in a two-dimensional framework, but the results of Kingsmill and Houze document that the same types of circulation features occur even if the MCSs do not take the form of two-dimensional squall lines.

In Figs. 4–6, we see a sequence of events similar to that of an individual MCS, but on a time scale corresponding to a 2–4-day equatorial wave—much longer than the time scale of an MCS. In addition, the peak statistical frequencies of occurrence of SCE, DCC, WCC, and BSR radar echoes follow a temporal sequence in line with these sounding data. That is, over the 2-day period of a precipitation episode, the convective statistics (not the individual convective cloud systems) indicate that the synoptic-scale conditions in the earlier part of the 2-day episode favor MCSs in their earlier stages of development and that as the 2-day period continues the large-scale conditions are increasingly favorable for the persistence and/or amplification of the later stratiform stages of development of individual MCSs. We may view this behavior of the echo statistics against the background of the evolution of the synoptic-scale environment. The synoptic-scale wave pattern constituting the environment of a convective population during a 2-day precipitation episode embedded in the active phase of the MJO systematically favors convection in early, middle, and late stages of development, respectively.

**FIG. 5.** As in Fig. 4b, but for divergence (shading, $10^{-6} \text{s}^{-1}$) and vertical velocity (contours, $10^{-3} \text{hPa s}^{-1}$; solid lines indicate positive values) anomalies calculated using ERA-Interim data.

**FIG. 6.** As in Fig. 4, but for composite time–height sections of zonal (shading, m s$^{-1}$) and meridional (contours, m s$^{-1}$; solid lines indicate positive values) wind anomalies.
Figures 4–6 show this progression over the 2-day period of the episode. Thus, we see that three scales are involved. The largest scale is the MJO, which establishes the possibility of a convectively disturbed environment. The intermediate scale is the 2-day period of a precipitation episode, where the time scale is probably controlled by an inertia-gravity wave or other synoptic-scale easterly wave passage. The smallest scale is the individual convective element. These elements are nearly always present and undergoing life cycles shorter than 2 days. During the passage of the intermediate-scale wave, the population of convective elements adjusts, with the early phase favoring a higher proportion of convective elements in earlier stages of development, the middle phase favoring a larger proportion of MCSs in middle stages of development, and the later phase allowing a larger proportion of the population to consist of MCSs reaching later stages of development.

These composite time series are thus consistent with the stretched building-block notion of Mapes et al. (2006), according to which the changing makeup of the ensemble of precipitating clouds over a time period greater than the time scale of individual cloud systems, such as the MJO rainfall episode considered here, coincides with a temporal sequence of wave-determined thermodynamic and dynamic variables analogous to but on a longer time scale than the life cycle sequence of an individual MCS. It seems unlikely that without a wave originating from some larger-scale dynamics, that such an orderly 2-day sequence of cloud population statistics could occur. However, as noted by Mapes et al. (2006), the convective population may well feed back positively to the wave structure and make this type of convectively coupled wave eminently more observable. Since the convective population is weighted toward a particular stage of convective development in a given larger-scale wave phase environment, it stands to reason that the particular stage of the convective population would imprint itself on the larger-scale wave in a positively reinforcing sense.

b. Spatial distribution of environmental properties at different times during rainfall episodes

To investigate how the synoptic conditions vary in space during the time periods of the precipitation episodes studied here, we have employed the ERA-Interim data (section 2). Figure 7 shows longitude–height composites of the reanalysis zonal–vertical wind, divergence, and specific humidity anomalies averaged over the 1.5°S–1.5°N latitude band at three representative times during the composite rainfall episode. The vertical wind is exaggerated 1000 times to allow a comparison with the horizontal wind.

At 24 h before the maximum in rain accumulation (Fig. 7a), low-level easterly wind and low specific humidity were present in the vicinity of the radar. At the same time, west of the radar location (around 65°E), there is a region of low-level convergence and positive anomalies of specific humidity. As time progresses from −24 to −6 h, the region west of the radar favoring moistening and low-level convergence moves eastward toward the radar region. By −6 h, the atmosphere around the radar location is moist, with strong vertical motion and low-level convergence (Fig. 7b). At this time, the upward motion associated with upper-level divergence penetrates to the highest level (up to 400 hPa) around the same time as the frequency of DCC events is greatest (Fig. 3). These behaviors are analogous to the early stage
of MCS development, but on a larger scale, and these time periods correspond to when DCCs and WCCs are more prevalent. From \( -6 \) to \( +12 \) h, the lower atmosphere cools and dries, and the low-level convergence decreases at the radar site (not shown). The region of high moisture, low-level convergence, and upward motion continues moving eastward, while in the region near the radar downward motion and divergence set in (Fig. 7c). Between \( +6 \) and \( +12 \) h the lower atmosphere has the lowest potential temperature and specific humidity anomalies. These later-period characteristics are analogous to BSRs in later stages of development with large stratiform rain areas. This time period is when BSRs are most frequent (Fig. 3).

6. Conclusions

This study has identified and examined the most extreme convective entities detected by the NCAR S-PolKa radar during the DYNAMO/AMIE field campaign. We have analyzed the S-PolKa three-dimensional reflectivity field to identify four basic types of echo objects, which have been used in previous studies to analyze TRMM satellite radar observations of deep convection over other regions of the earth (Houze et al. 2007; Romatschke and Houze 2010; Rasmussen and Houze 2011; Barnes and Houze 2013). The satellite data are in the form of snapshots, which make the results difficult to interpret with certainty. Our study applies this approach to temporally continuous ground-based radar data, and the results verify interpretations made in studies using TRMM data. In addition, the results provide insight into the nature of the convective cloud populations producing MJO rainfall episodes over the Indian Ocean.

From October 2011 through early January 2012, three main active phases of the MJO occurred, and within these active phases, the rain in the vicinity of the S-PolKa radar was concentrated in 11 episodes separated by 2–4 days—much shorter periods than the time scale of an MJO active stage, yet longer than the time scale of individual convective elements or systems. This 2–4-day modulation likely is due to westward-propagating synoptic-scale equatorial waves. We performed a running mean to highlight the 11 episodes and identify their times of peak rainfall accumulation over the area observed with S-PolKa. We have shown that each of the 11 rain episodes was characterized by an ensemble of deep convection that went through a sequence of statistical states such that each statistical state was dominated by convective systems in successively later stages of development:

- Shallow convective echoes were almost always present before, during, and after the time of the peak in rain accumulation. However, their frequency was maximum about 12 h prior to the time of maximum rain accumulation, then reached a minimum at the peak of the rain episode, and after, their frequency of occurrence recovered toward the end of the 2-day period.
- The number of deep convective cores tended to increase as the frequency of shallow echoes decreased. The deep convective cores reached a maximum at 5–10 h before the peak in rainfall accumulation.
- The number of wide convective cores was at a maximum around the time of maximum rain accumulation.
- The frequency of broad stratiform regions maximized several hours after the maximum of rain accumulation.

At any given time the cloud population produces echo elements of all four types, but the frequencies of each echo type maximize in the above order. Since mesoscale convective systems (Houze 2004) begin with an outbreak of convective cells, then grow upscale to mesoscale proportions as the cells aggregate into horizontally contiguous mesoscale units, this sequence of statistical states relative to the time of maximum rainfall accumulation implies that prior to the rain maximum the environment favors a population of intense convective elements that has a predominant proportion of intense convective elements in formative and growing stages. During the period of peak rainfall, the environment allows the population of convective elements to have a higher proportion of wide convective cores (i.e., more convection forming into MCSs). As the rain accumulation drops off in the later part of the rainfall episode, the environment is permitting the cloud population to have a higher proportion of echo elements in the form of broad stratiform regions, indicating that in this later period the environment is allowing a greater proportion of the echo elements in the form of MCSs to reach their later stages of development. The convective population likely feeds back to the environment, reinforcing the conditions controlling the nature of the population at any given time relative to the center time of the rain episode.

To gain insight into this concurrent systematic variation of the environment and convective population statistics over the 2-day rain episodes occurring in the active period of MJOs, we composited both the Gan sounding and ERA-Interim variables to investigate the connection of the changing cloud population to the large-scale environment during the 11 MJO rainfall episodes. The results show unstable conditions in the early part of the rainfall episode, when SCE and DCC echoes were most frequent. By the time of the maximum rainfall, the cloud population was dominated by WCC echoes, which are a signature of the presence of a maximum number of
mature MCSs. The large-scale vertical motion was a maximum at this time, with a pronounced convergence signature at low levels. During the period of declining rain accumulation over the radar area, stabilization occurred, and the large-scale mean motion was downward in the mid- to low troposphere, with strong divergence at low levels. These stages are analogous to the life-cycle stages of an individual MCS, but they manifest on a longer time scale and over a bigger area than an individual system. These stages probably correspond to equatorial waves superimposed on the MJO environment. The divergence sequence of the composite is consistent with the sequence expected of a westward-propagating inertia-gravity wave (Haertel and Kiladis 2004; Kuang 2008; Kiladis et al. 2009) with other longer-period synoptic-scale waves likely mixed into the composite but hard to separate within the limited sample of data. Thus, the large-scale environment and convective population exhibit characteristics consistent with the stretched building-block hypothesis of Mapes et al. (2006). Coincident with the membership of the cloud population changing from an ensemble containing a predominance of young deep but relatively separate convective cells to a population dominated by mature MCSs to a population with older MCSs with large stratiform regions, the large-scale conditions take on the aspect of a “stretched” analog to the typical MCS life cycle. Hours before the maximum in rain accumulation, when the ensemble is dominated by SCEs and DCCs, the surface westerly wind and convergence increase, the atmosphere warms and becomes moister, and the CAPE reaches a peak; that is, the environment is favorable for deep convection to occur. When WCCs become most frequent near the time of the peak of the rainfall episode, upward motion maximizes. Then as BSRs have their greatest frequency, stabilization occurs, evaporative cooling increases, and low-level convergence and upward motion decrease and reverse to downward motion and low-level divergence. This simultaneous behavior of the convective population and synoptic-scale environment is entirely consistent with Mapes et al.’s (2006) hypothesis of a “natural selection” in the atmosphere for waves whose phases produce a local Eulerian sequence of structures aligning with convective life-cycle behavior.

Studies using TRMM satellite radar data to examine the climatology of deep convection have compiled statistics of DCCs, WCCs, and BSRs and have speculated that when statistical maxima of these echo types occur in a sequence of geographical locations, the locations of the maxima indicate regions where mesoscale convective systems tend to form, mature, and dissipate, respectively. However, since the TRMM orbits obtain only snapshots of the radar echo pattern at widely separated times, it has not been possible to verify these speculations. The time continuity of the ground-based S-PolKa radar used in the present study has been able to determine that the statistical maxima of DCC, WCC, and BSR frequencies do indeed occur in a temporal sequence consistent with mesoscale convective system life-cycle stages. In a concurrent study, Barnes and Houze (2013) are using 14 years of TRMM radar snapshots to identify isolated shallow echoes, DCCs, WCCs, and BSRs over broad expanses of the Indian and western Pacific Oceans during different phases of the MJO. Our study provides ground validation for that climatological investigation by making it possible to interpret the concentrations of each of the echo types seen by the TRMM radar as representative of life-cycle stages of the deep convection–producing precipitation in the MJO. Such satellite datasets are a primary pathway for upscaling results from the DYNAMO/AMIE field project to the scale of the MJO and in turn for providing observational information for modeling studies aimed at understanding the coupling of convection to the large-scale circulation of the MJO.

The S-PolKa radar data collected in DYNAMO/AMIE have the potential to add information that will further underpin satellite interpretations of the MJO radar echo climatology. A further strength of the S-PolKa radar is that it can use its S-band dual-polarimetric capability to identify the dominant hydrometeor types producing the radar echoes. The scanning strategy of the S-PolKa radar (section 2; Fig. 1c) was designed to optimize the information on hydrometeor types by applying techniques such as that of Vivekanandan et al. (1999) to deduce the most probable vertical profiles of hydrometeor types in each echo seen by the radar. In a future article, we will apply such methods to the echo types identified in this study. That future article will enhance the basic echo-type results of the present study with information on the microphysical processes most responsible for producing the precipitation in the early, middle, and late stages of the active phases of the MJO rainfall episodes. The results of the present and future studies of data collected by the S-PolKa radar in DYNAMO/AMIE will thus provide information on the nature of MJO convection that will help guide numerical simulations of global and regional models used to simulate and forecast MJO behavior.

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